

MIMO Antennas for Mobile Terminals

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Abstract—Recently, Multiple-Input and Multiple-Output (MIMO) technology has attracted much attention both in industry and academia due to its high data rate and high-spectrum efficiency. By increasing the number of antennas at the transmitter and/or the receiver side of the wireless link, the diversity/MIMO techniques can increase wireless channel capacity without the need for additional power or spectrum in rich scattering environments. However, due to the limited space of small mobile devices, the correlation coefficients between MIMO antenna elements are very high, and the total efficiencies of MIMO elements degrade severely. Furthermore, the human body may give high absorbance of electromagnetic waves. During application, the presence of users may result in the significant reduction of the total efficiencies of the antenna and highly affects the correlations of MIMO antenna systems. In this review paper, recent technologies that aim to improve MIMO antenna performance are reviewed for mobile terminals. The interactions between a MIMO antenna and human body are also reviewed for mobile terminals.

Index Terms—MIMO, diversity, antenna array, mobile handset antenna, UWB, user effect, specific absorption rate.

I. INTRODUCTION

Public demands for faster transmission and reception of information are endless and have been the driving force behind the progress of wireless technology. Since 1985, wireless communication systems have rapidly evolved from analog systems (1G: first-generation systems) to digital systems (2G: second-generation systems), and later to third-generation systems (3G), which can realize multimedia transmission. In order to further increase the data transmission rate, multiple-input and multiple-output (MIMO) technology has become an important feature in fourth-generation (4G) wireless communication systems. As “a key to gigabit wireless” [1], MIMO can linearly increase channel capacity with an increase in the number of antennas, without needing additional bandwidth or power [2]–[4]. Moreover, popular wireless communication systems typically operate in a rich scattering environment, which

MIMO exploits to achieve the large performance gain demanded. A multiple antenna system can operate in diversity or MIMO schemes according to the SNR level under rich scattering circumstances [71]. If the SNR is low, the diversity can be applied to combat the fading. All the antenna at the transmitter (or receiver) send (or receive) the same signals over the same channel. Since the transmitting (or receiving) antennas are uncorrelated, the possibility of the fading deeps for all the antennas is reduced. The reliability in the wireless link is improved. In the high SNR region, the MAS will work in the MIMO scheme and utilize the fading to provide several uncorrelated channels. The different data are simultaneously transmitted over different channels with the same operating frequency, where the maximum data rate is achieved.

However, due to the limited space of small mobile devices, the correlation coefficients between MIMO antenna elements are very high, and the total efficiencies of MIMO elements degrade severely.

Furthermore, the human body may significantly absorb electromagnetic waves. During application, the presence of users may result in the significant reduction of the total antenna efficiencies and highly affects the correlations of MIMO antenna systems. Mobile terminals need to fulfill different standards. For instance, RF over-the-air (OTA) performance of mobile phones with user impact is required by many telecommunication operators. In addition, the Specific Absorption Rate (SAR) of a mobile terminal shows the amount of RF radiation emitted by a radio to a human body. SAR values of mobile terminals are strictly limited by governments. With MIMO technology, the channel capacity of a system can be enhanced but the complexity of the SAR issue will be increased accordingly.

The multiband internal antenna design and bandwidth enhancement technologies have been deeply discussed in [5]–[10]. Various MIMO antennas for portable devices have been studied in [13]–[48]. In the paper, we will review some key technologies for mobile terminal MIMO antennas. The effect of the human body and the SAR issues of MIMO cellular antenna will also be addressed in the paper.

This paper is organized as follows: In Section II, important parameters for a MIMO antenna system will be introduced. Mobile terminal MIMO antennas and their

interactions with human body will be reviewed in Section III and Section IV, respectively. Finally, the conclusion and future directions of MIMO antenna research will also be provided in Section V.

II. IMPORTANT PARAMETERS FOR MIMO ANTENNAS

The correlation of a multiple antenna system is used to describe the degree of independence of the different antenna ports. The envelope correlation coefficient (ECC) ρ_e is given in [11]:

$$\rho_e \approx \frac{\int \left(XPR \cdot E_{\theta X} E_{\theta Y}^* P_{\theta} + E_{\phi X} E_{\phi Y}^* P_{\phi} \right) d\Omega}{\sqrt{\int \left(XPR \cdot E_{\theta X} E_{\theta X}^* P_{\theta} + E_{\phi X} E_{\phi X}^* P_{\phi} \right) d\Omega \int \left(XPR \cdot E_{\theta Y} E_{\theta Y}^* P_{\theta} + E_{\phi Y} E_{\phi Y}^* P_{\phi} \right) d\Omega}} \quad (1)$$

where $E_{\theta, \phi X}$ and $E_{\theta, \phi Y}$ are the embedded, polarized complex electric field patterns of two antenna X and Y, respectively, in the multiple-antenna system. XPR is the Cross Polarization Ratio. A good rule of thumb for strong diversity/MIMO performance is $\rho_e < 0.5$. When MIMO antenna elements are lossless, ρ_e can be estimated by S parameters [60]. In practice, if MIMO antenna elements have high radiation efficiency [50] and are well matched to 50- Ω impedance, a low envelope correlation coefficient can be achieved by mutual coupling reduction (or isolation enhancement). Please note that the mutual coupling (or isolation) mentioned in this paper refers to S21 in S parameters.

For a multi-port antenna system, when only one port is fed and the others are terminated with a 50- Ω load, the total efficiency can be evaluated by the following equations:

$$\eta_{total} = \eta_{radiation} \eta_{mismatching+coupling}$$

$$\eta_{mismatching+coupling} = 1 - |S_{ii}|^2 - \sum_{j \neq i} |S_{ji}|^2 \quad (2)$$

where η_{total} , $\eta_{radiation}$ and $\eta_{mismatching+coupling}$ are the total efficiency, radiation efficiency, and the efficiency of mismatching plus mutual coupling, respectively. Subscripts i and j represent the operating and terminated ports, respectively. According to Eq. (2), mutual coupling can lead to a decrease in total efficiency.

In order to simply evaluate MIMO performance, the multiplexing efficiency (MUX) of a MIMO antenna was recently defined [12] as follows:

$$\eta_{mux} = \sqrt{\eta_1 \eta_2 (1 - \rho_e)}, \quad (3)$$

where η_1 and η_2 are the total efficiencies of the MIMO antenna elements.

III. MIMO ANTENNAS FOR MOBILE TERMINALS

In current and future wireless telecommunication systems such as the long-term evolution (LTE) and LTE-Advanced, multiple-input and multiple-output (MIMO) systems are an integral part of mobile terminals. In LTE standards, several new channels are allocated to the lower bands of 700-960MHz. The elements in the MIMO antenna system should have a low correlation and a high total efficiency to guarantee good multiplexing MIMO performance. Generally,

unlike the higher bands, the mobile handset MIMO antenna system operating in the lower frequencies will not focus on the reduction of the mutual coupling, but rather, the direct improvement of the correlation and efficiency due to the low radiation efficiency [50]. The wavelengths in the lower frequencies are much longer than those in the higher bands, and this poses some new challenges on the practical realization of good MIMO performance in mobile terminals: (1) each MIMO antenna element has to be redesigned to obtain a compact structure of the device; (2) the structures for decorrelation have to be small enough and still work well; (3) the MIMO elements and the decorrelating structures are more closely positioned, causing high correlation and low efficiencies; and (4) the chassis mode will be efficiently excited, which makes the radiation pattern of each MIMO element quite similar, leading to a very high correlation. An envelope correlation coefficient less than 0.5 and a total efficiency higher than 40% are good values for a cellular LTE MIMO antenna in the lower bands, according to industry research, including field trials and mock ups [49]. Some studies have been done trying to solve these problems, such as the neutralization line method, for a single-band LTE MIMO antenna in [43] and [44], as well as decoupling networks for the lower bands in [35], [36] and [45]. However, these methods can only be used for very narrow bands and will cause a large radiation efficiency reduction in practice. In the following, we will review the recent technologies for reducing correlation and improving total efficiency in lower bands (less than 1 GHz).

A. Chassis mode and orthogonal chassis mode MIMO antenna

In [51], the interactions between a MIMO antenna and mobile chassis have been studied. The E field and H field of the fundamental mobile chassis characteristic mode is given in Fig. 1. The results reveal that the characteristic modes play an important role in determining the optimal placement of antenna. For example, if two electric antenna are put at the two ends of the mobile chassis, a very high mutual coupling between two antennas can be expected.

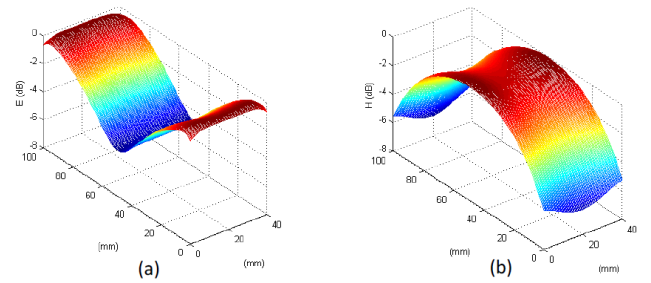


Fig. 1. Characteristic mode of mobile chassis: (a) E field, and (b) H field [51].

In mobile terminals, the orthogonal mode MIMO antenna can be realized by combining an electrical antenna (dipole) and a magnetic antenna (slot, loop) [52], based on the analysis in [51]. The prototype of the design orthogonal mode MIMO antenna is presented in Fig. 2. Since the radiation efficiency of this design is high, correlation and total efficiency can be improved if the mutual coupling between MIMO elements is reduced. A very low mutual

coupling has been achieved in a narrow band in lower frequencies for the proposed antenna, as shown in Fig. 2.

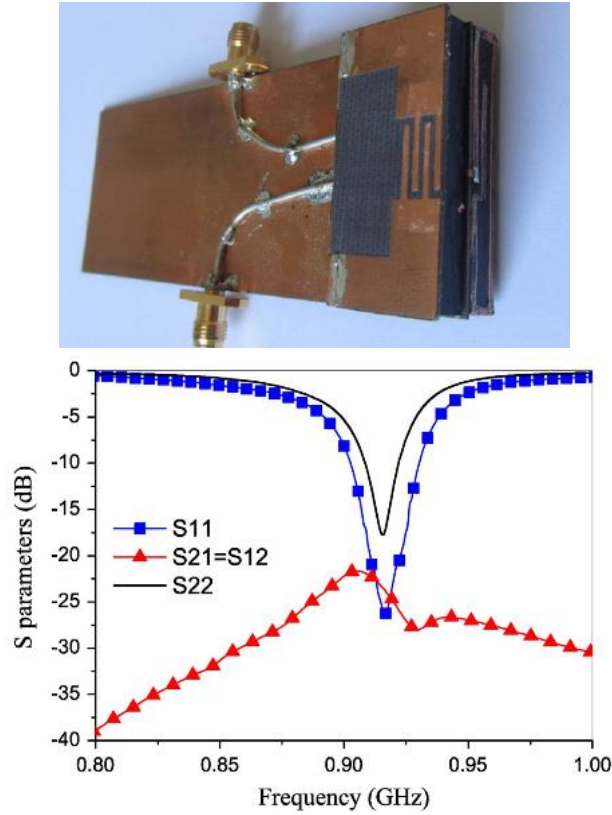


Fig. 2. Orthogonal mode MIMO antenna and its measured S-parameters [52].

B. Localized Mode

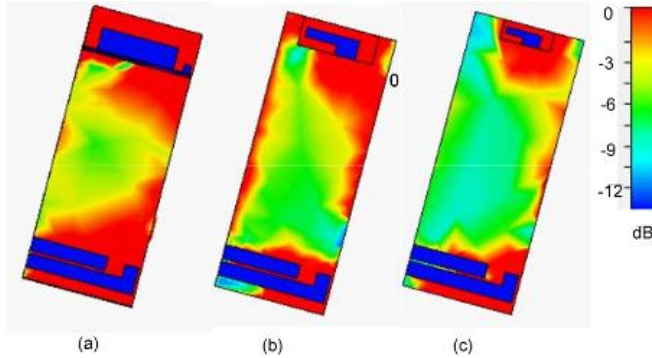


Fig. 3. Normalized magnitude of current distributions for PIFA with: (a) $\epsilon_r=1$, (b) $\epsilon_r=6$, and (c) $\epsilon_r=20$ [53].

In some cases, when two electrical MIMO antenna elements are used in a mobile terminal, good diversity and decoupling performance can be achieved by exciting different modes for different antennas. For example, Antenna 1 is excited in the chassis mode, whereas Antenna 2 is excited in the localized mode [53]. Typical directive antenna such as patch, notch and balanced dipoles are good candidates to be excited in localized mode. Fig. 3 shows the current distributions of PIFA with varying dielectric permittivity. With a higher dielectric permittivity, the current of PIFA is more localized.

C. Mutual scattering mode and diagonal antenna-chassis mode for MIMO bandwidth enhancement

In order to realize a correlation less than 0.5 and total efficiency higher than -4 dB in a wideband of low frequencies, the mutual scattering modes [54] [55] and diagonal antenna-chassis modes [56]-[58] were published for MIMO bandwidth enhancement.

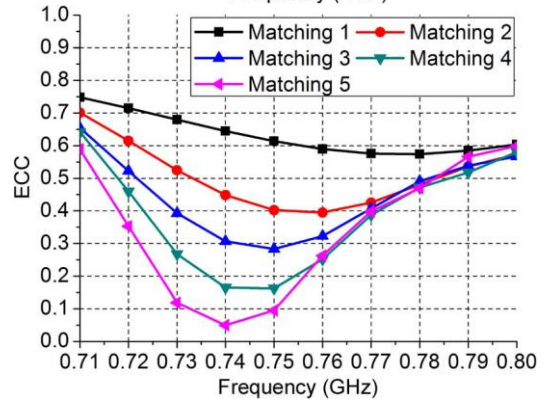
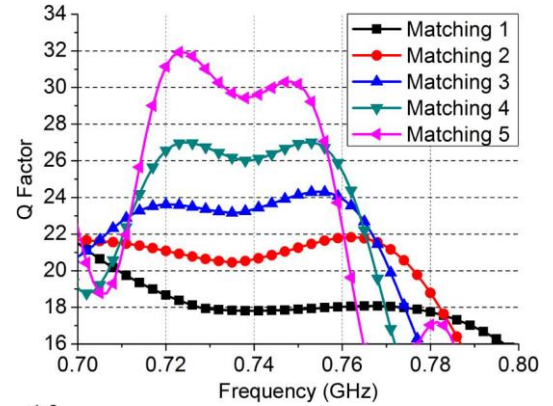
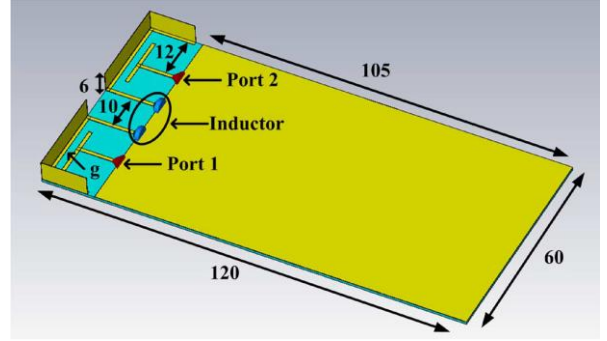


Fig. 4. Mutual scattering mode in mobile terminals [55].

For closely located MIMO antenna, the strong mutual scattering effect can be used to reduce the correlation coefficient of the MIMO antenna [54] [55]. In general, MIMO antennas with high Q values will have a strong mutual scatter effect, which can be realized by optimizing impedance matching with lumped elements. In Fig. 4, it is revealed that when two antennas are put in the same end of the mobile terminal, a higher Q factor could provide a lower correlation with an improved total efficiency. The Q factors in Fig. 4 are obtained according to [72, Eq. 96]. The resistance and reactance of the input impedance required in

[72, Eq. 96] is calculated by [73, Eq. 10], where the non-operating port is terminated with a 50 ohm load. In addition, a MIMO reference antenna based on the mutual scattering mode was proposed in [61] for OTA applications.

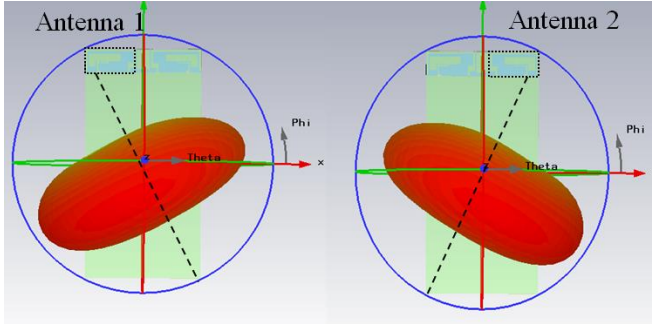


Fig. 5. Simulated diagonal chassis mode in mobile terminals [58].

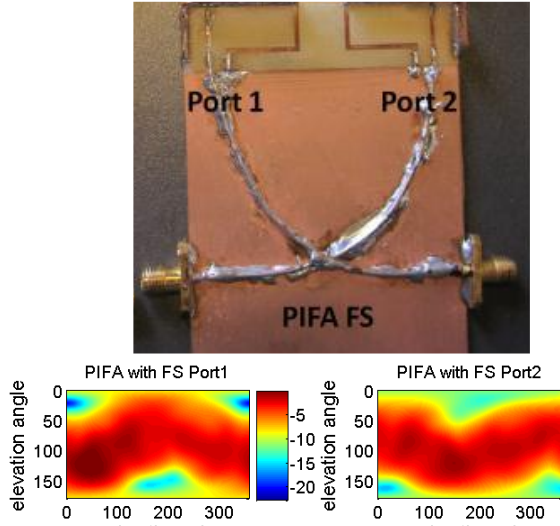


Fig. 6. Prototype and measured radiation patterns for the diagonal chassis mode study in mobile terminals [58].

Combined with a diagonal chassis mode, better pattern diversity can be achieved in the low LTE band (<1GHz) [56]-[58]. When a terminal antenna operates at low frequency, the antenna element and the ground plane can be seen as two arms of a dipole antenna. Thus, the direction of the radiation pattern of this dipole antenna will be determined mainly by the current distribution on the ground plane. This is because the volume of the ground plane is much larger than that of the antenna element. The diagonal chassis mode can be realized by placing the two antenna ports of a dual-element MIMO antenna at different corners of the ground plane. As a result, the two MIMO elements can form two orthogonal dipole-like radiation patterns. In Fig. 5 and Fig. 6, we can see that a co-located MIMO antenna has almost opposite patterns due to the effect of the diagonal chassis mode.

D. Correlation coefficient calculation with S parameters and radiation efficiency

In a lossless MIMO antenna system, the correlation coefficient can be estimated by calculating the S parameters [60]. By taking the radiation efficiency into account, the upper bound of the correlation can be calculated [50]. The

authors in [59] use an equivalent circuit-based method to calculate the correlation in lossy antenna arrays. The equivalent circuit is shown in Fig. 13, where a lossy component is introduced to simulate the loss. A more accurate estimation of the correlation can be obtained, compared with the methods in [50] and [60].

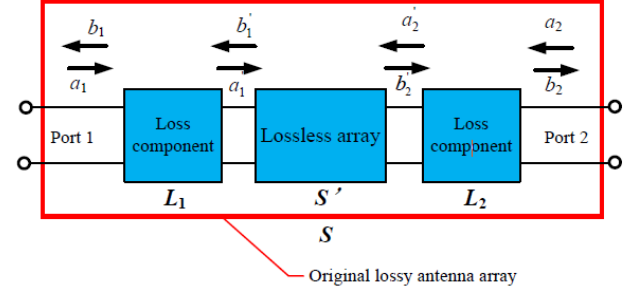


Fig. 7. Correlation coefficient calculation with S parameter and radiation efficiency.

IV. INTERACTIONS BETWEEN MOBILE TERMINAL MIMO ANTENNAS AND THE HUMAN BODY

A. The Body Effect on Compact MIMO antennas in Mobile Terminals

The radiation performance of MIMO antennas in mobile terminals, including user effects, is another important issue. Test regulations for mobile terminals in the user case have been developed or are ongoing. The Cellular Telecommunications and Internet Association (CTIA)/The Wireless Association is a United States-based international organization that serves the interests of the wireless industry by lobbying government agencies and assisting with regulation settings [62]. To date, two user cases have been defined by CTIA in the OTA test of mobile terminals, which are the talking mode (head + hand) and the data mode (single hand) shown in Fig. 8.

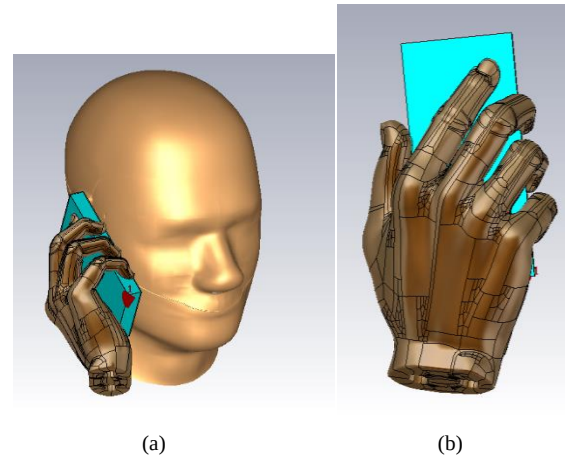


Fig. 8. CTIA user cases: (a) the talking mode and (b) the data mode.

For the user case, both the correlation coefficient and total efficiencies of MIMO terminal antenna are low in general.

The substantial loss of total efficiency is mainly due to the mismatch and reduction of the radiation efficiency of the antenna (due to body absorption). The mismatch can be resolved by tuning the operating frequency of the antenna with lumped elements, but the drop in radiation efficiency is not as easily prevented.

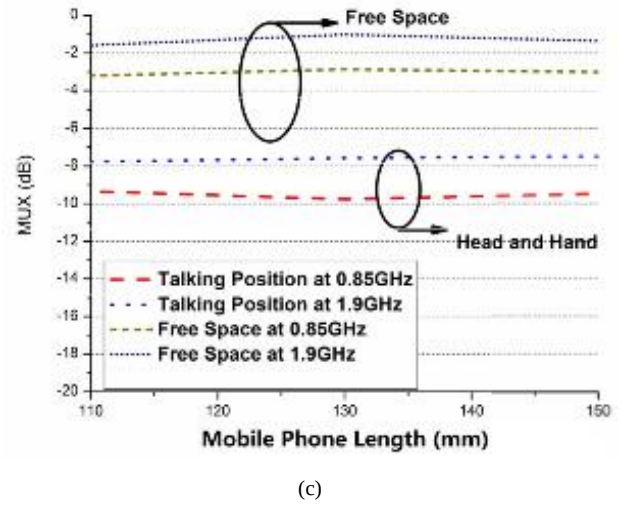
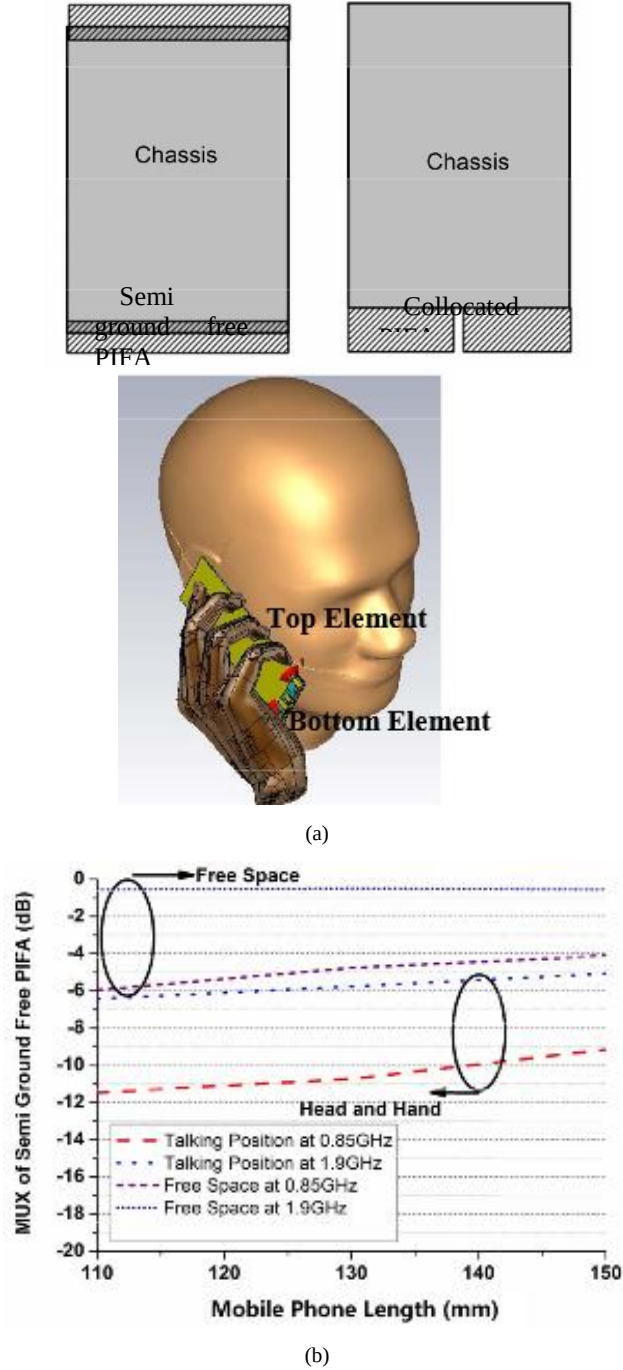
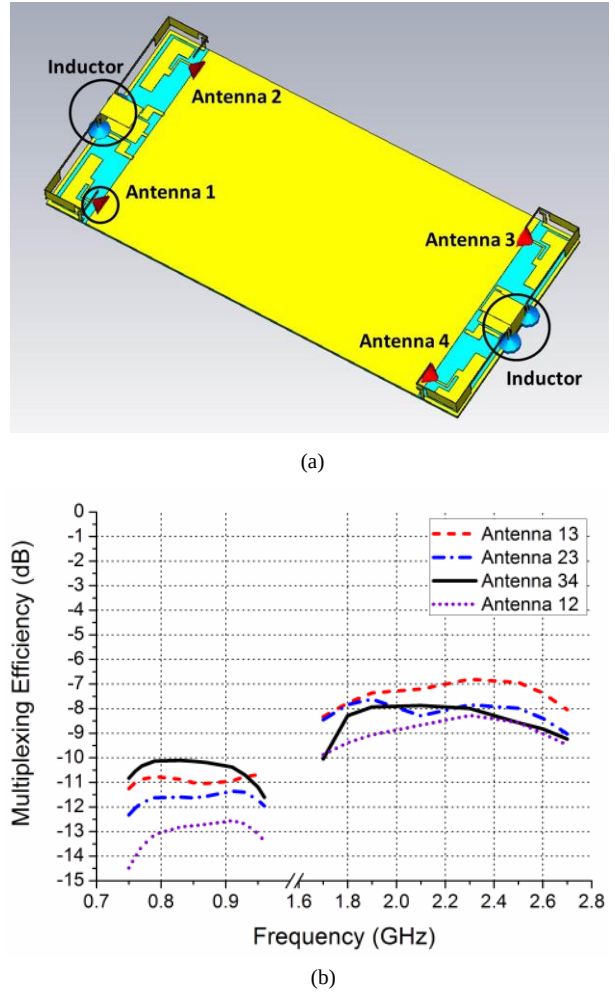


Fig. 9. The impact of different MIMO antenna and chassis lengths on the body loss of the talking mode in [70]: (a) setup, (b) MUX of semi ground-free MIMO PIFA, and (c) MUX of collocated MIMO antenna.



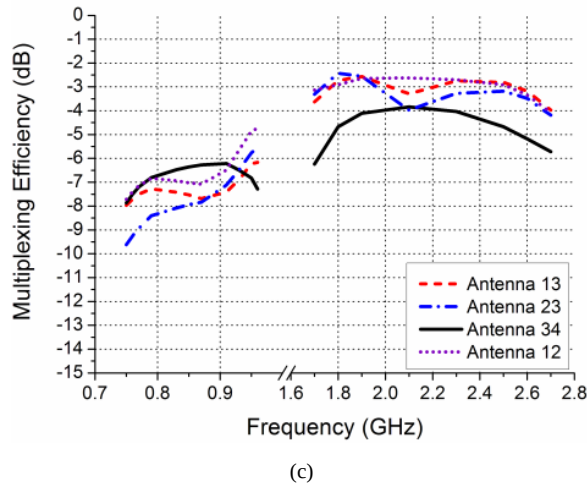


Fig. 10. User-effective adaptive quad-element MIMO antenna, (a) antenna configurations, (b) MUX of adaptive MIMO antenna in talking mode, and (c) MUX of adaptive MIMO antenna in data mode. [65]

The efficiency loss of MIMO terminal antennas depends on several factors, including antenna locations, operation frequencies, phone size, etc. [63] [70], as shown in Fig. 9. Several methods have been proposed to minimize the body loss in MIMO terminal antennas. In [64], by introducing a small space between the human body and antenna, the hand-effect body loss for LTE mobile antenna can be reduced significantly in CTIA talking and data modes. In [65], an adaptive quad element MIMO antenna array is designed (Fig. 10). Here the body loss can be optimized and the MIMO performance can be enhanced by selecting the best two elements out of four when the terminal is held by users.

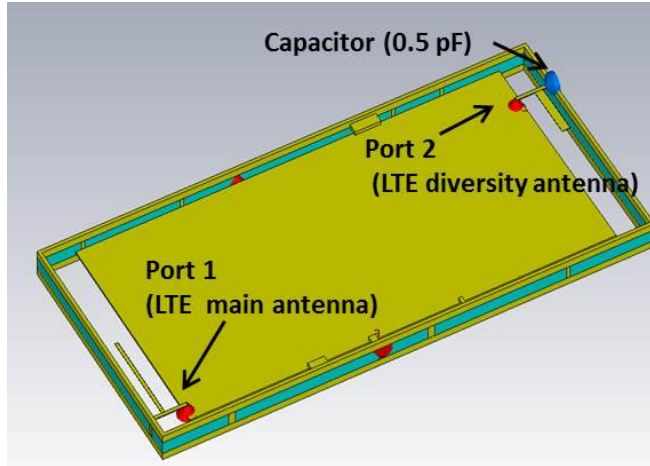
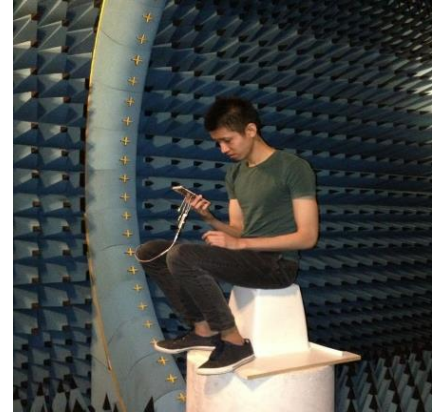


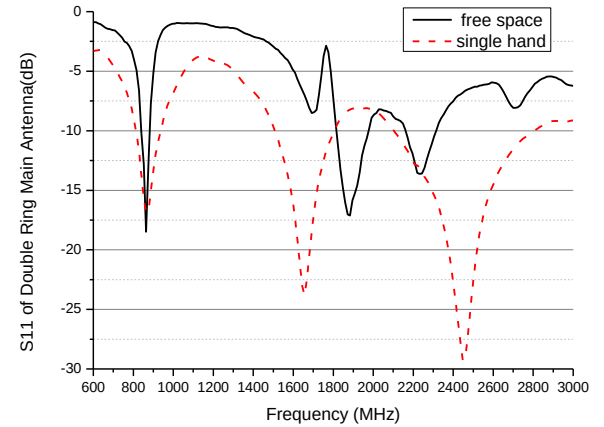
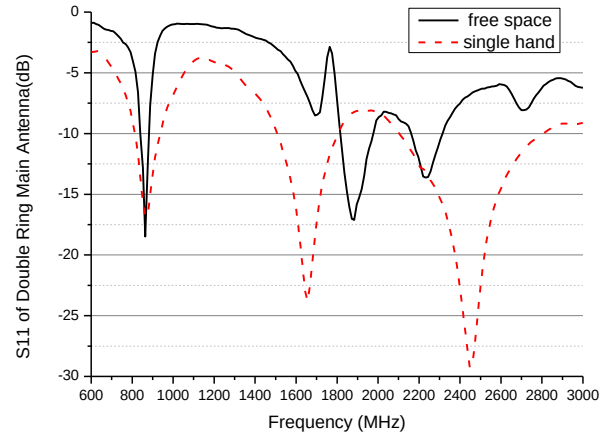
Fig. 11. Double ring antenna.

Since the human body is insensitive to magnetic fields, the author in [66] proposed a novel mobile terminal antenna named the double ring antenna, which is mainly based on a magnetic loop mode (Fig. 11). The double ring antenna are measured in a real person setup (see Fig. 12 (a)). The comparison of single hand effects on S parameters between the double ring antenna and conventional design are shown in Fig. 12 (b). The average total efficiency loss on the single hand is presented in Table 1. All the results show that the double ring antenna is able to maintain relatively high total

efficiencies in a user case when compared to other conventional MIMO antenna in mobile terminals.



(a)



(b)

Fig. 12. Double ring antenna under field test: (a) measurement setup and (b) the comparison of single hand effects on S parameters between the double ring antenna and conventional design.

Table I Average total efficiency loss on single hand

TE loss in talking mode (dB)	Main antenna of DR	Main antenna of CA
Left side in lower band	6,44	8,39
right side in lower band	9,02	9,38
Left side in higher band	5,29	11,61
right side in higher band	5,31	6,87

B. The SAR performance of Compact MIMO antenna in Mobile Terminals

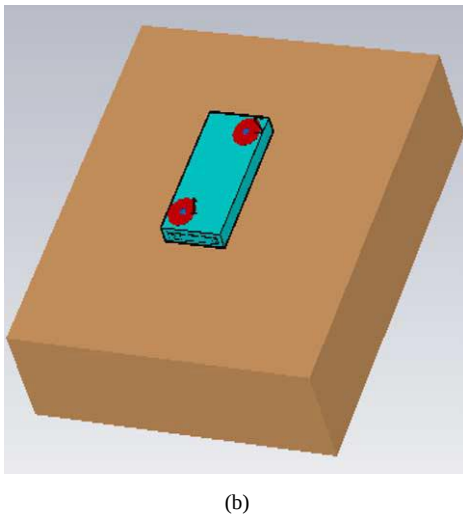
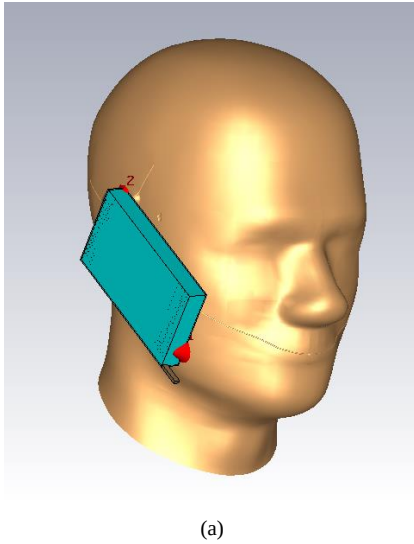


Fig. 13. SAR test positions: (a) SAM head phantom and (b) flat phantom.

SAR is the value that indicates RF radiation from a mobile phone to a human body, and the radiation mainly comes from the antenna. The unit of SAR is watts per kilogram (W/kg). The SAR value of a mobile terminal is strictly limited by governments, which makes this parameter important in mobile antenna designs. There are two main SAR standards: in Europe, the limitation of SAR is set to be 2.0 W/kg over a 10-g cube by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) Organization; in the United States, the Federal Communication Commission (FCC) set the limitation to be 1.6 W/kg over a 1-g cube. The SAR value must be measured on a Specific Anthropomorphic Mannequin (SAM) head phantom and flat phantom (Fig. 13), for the talking case and the carrying case, respectively.

For the MIMO antenna, the evaluation of SAR becomes more complicated. Just the stand-alone SAR is not sufficient to evaluate SAR performances of MIMO antennas. Simultaneous SAR is required when multiple antenna are transmitting simultaneously, which requires adding up the SAR fields of the two ports and calculating the combined peak SAR value.

In order to simplify the SAR evaluation of a MIMO antenna in a mobile terminal, the value of the SAR to PEAK location spacing ratio (SPLSR) is defined by the FCC as [67]:

$$SPLSR = (SAR1 + SAR2)/D \quad (4)$$

where SAR1 and SAR2 are SAR values (W/kg) of Elements 1 and 2, respectively, and D is the separation distance (cm) of the two SAR peaks, as illustrated in Fig. 14.

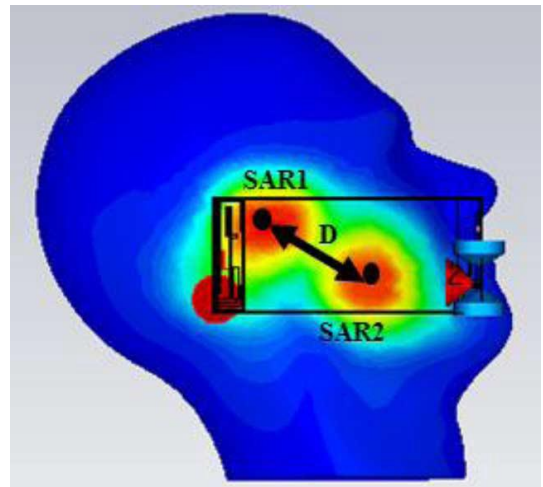


Fig. 14. The illustration of the SAR to PEAK location spacing ratio (SPLSR).

According to FCC standards, simultaneous SAR measurement of a phone is not necessary if the SPLSR is smaller than 1.6 [67]. From (2), it is clear that the length of the ground plane plays an important role for simultaneous SAR. On one hand, a proper ground plane length can excite the chassis mode, which will reduce the peak value of stand-alone SAR; on the other hand, the strong chassis mode could

reduce the separation distance between the two SAR peaks as the peak position of SAR will move to the center of the ground plane, which could enhance simultaneous SAR [68]. Apart from the ground plane length, antenna types also have significant impact on the SAR value, as shown in Fig. 15. From the engineering point of view, a ground-free antenna is always (with high SAR) located at the bottom of the phone, whereas an on-ground antenna (with low SAR) will be put on top of the phone to reduce correlation. The flat phantom SAR can be measured with the iSAR system in Fig. 16. The comparison between simulated and measured SAR distribution (dB) for semi ground-free PIFA at 10mm above the flat phantom are presented in Fig. 17 [68].

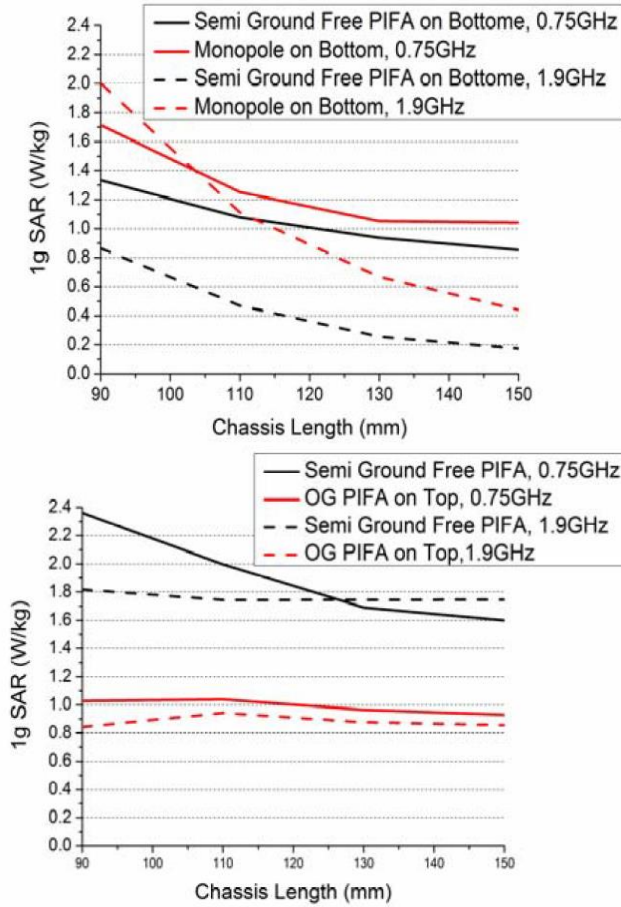
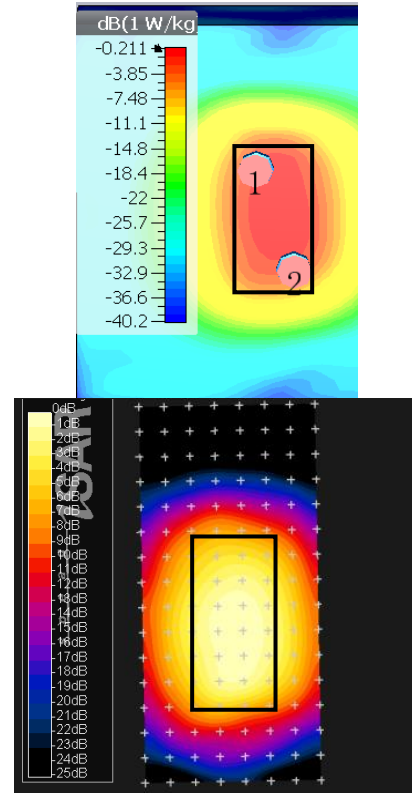


Fig. 15 Simulation SAR with varying antenna type and chassis length.



Fig. 16 The measurement setup of the iSAR system.



(a)

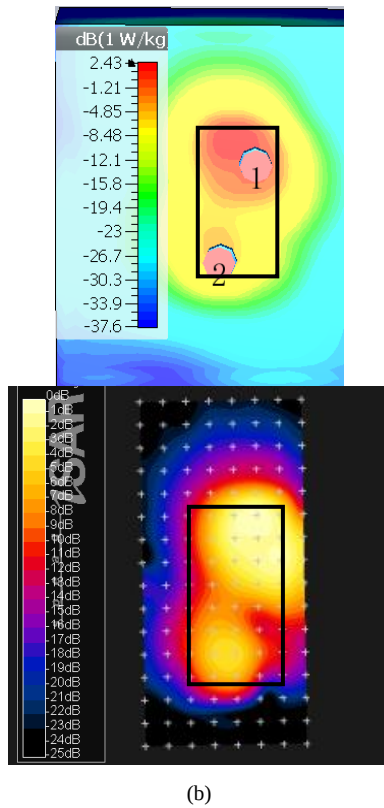


Fig. 17 The comparison between the simulated and measured SAR (dB) distribution (dB) for a semi ground-free PIFA at 10mm above the flat phantom at (a) 0.85GHz and (b) 1.9GHz.

V. CONCLUSION AND FUTURE DIRECTIONS OF MIMO ANTENNAS

In this paper, recently developed technologies for the improvement of MIMO antenna performance have been reviewed for portable devices and mobile terminals. Furthermore, the interactions between MIMO antenna and human body have also been reviewed for mobile terminals. The body loss and SAR reduction methods in some of the previous literatures have been introduced.

The future directions of MIMO antennas will focus on how to further increase the channel capacity for the fifth-generation (5G) application. High order MIMO or massive MIMO is one of the most promising direction. Theoretically, MIMO channel capacity increases linearly as the number of MIMO elements. With a large number of MIMO elements, some new phenomena have not been detailed investigated. Another possible direction is high frequency centimeter and millimeter wave band space multiplexing and beamforming. MIMO technology will be applied to the frequencies higher than the current (normally lower than 3 GHz). In the millimeter wave band, path loss is much higher than the low band. It requires the transmitting and receiving antennas have high gain and also pointing as each other to overcome the path loss. Based on these requirements, how and when to apply space multiplexing and beamforming are quite interesting topics.

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